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Minimum Quantity Lubrication (MQL) in Automotive Powertrain Machining

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Abstract

This paper summarizes the advancements and challenges of minimum quantity lubrication (MQL) technology in automotive powertrain machining from both industrial and academic perspectives. MQL refers to applying a small amount of cutting fluid in the form of mist to the cutting zone rather than flooding the workpiece. Elimination of coolant systems creates significant saving from energy and equipment, the flexibility to relocate the machines, reduction of waste stream and floor space, and a cleaner and healthier work environment. Ford Motor Company has demonstrated these advantages, and currently has a total of over 400 MQL CNC machining centers in numerous global transmission and engine plants running MQL operations, with further implementation planned for new programs globally. Technical challenges to realize 100% implementation includes tool design, delivery system, chip management, and thermal related problems, particularly in high-energy density processes and difficult-to-machine metals, such as deep-hole drilling and compacted graphite iron (CGI). This paper provides a review of current status and limitations of MQL machining and highlights opportunities for research and development of the next-generation MQL technology in automotive powertrain machining.

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1. Introduction

Minimum quantity lubrication (MQL), as its name implies, uses the smallest amount of metal working fluid (MWF) to achieve lubrication during machining processes. This technology has revolutionized the automotive powertrain production in the past decade. With the close collaboration among automotive, machine tool, tooling, and fluid delivery system manufacturers, MQL has demonstrated in multiple worldwide plants with better quality, higher productivity, minimal environmental impact, lower operation health issues, reduced water and greenhouse gas emission, and reduced energy consumption, which result in lower overall costs. An official report from German government for a project called "Research for tomorrow's Production", which involved several large companies like Bosch and Daimler, has indicated MQL's capability and cost-saving [1]. In North America, Ford Motor Company Powertrain Manufacturing launched its first MQL mass production program in May 2005. Since then, valve bodies, torque converter housings, and transmission cases have been machined with this green factory approach at two North American transmission plants. Due to the success of this technology and the benefits cited above, MQL is the standard, Bill of Process (BOP) machining method in Ford for aluminum transmission prismatic parts, gray iron and aluminum engine blocks, aluminum engine heads, and crankshaft oil and cross holes. The BOP is comprised of detailed plans explaining the manufacturing processes for a particular product, including process sequence and capital equipment. For any new Ford powertrain machining facility worldwide, machinery, equipment layout,

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configurations, tools, and instructions are all built based on MQL operation.

Sustainability is one of the major advantages offered by MQL [2]. Sustainability in machining processes is heavily influenced by its associated MWF technology. Global research started in the early 1990s to investigate technologies to reduce the costs and environmental impact associated with conventional flood coolant methods. Traditional machining processes use flood cooling to lubricate the cutting tools, remove chips, and to reduce thermal expansion of the workpiece, fixture, and machine. The flood MWF is an emulsion of water and an "oil" – typically a synthetic formulation. The flow rate is typically about 20 L/min, delivered to the cutting zone at pressures up to about 70 bar (or 1,000 psi.) Flood MWF systems require significant plant infrastructure for delivery, reclamation, filtration, chilling, and waste-water treatment. Furthermore, the systems demand constant monitoring and treatment to control fluid concentrations and to avoid fungal and bacterial growth. Worldwide, manufacturers currently consume over two billion liters of water-based and straight-oil MWFs each year, which creates a significant demand for non-renewable feedstock [3]. A study conducted at several powertrain plants of Ford identified annual coolant usage in excess of five million gallons and costing millions of US dollars [4]. To address these issues, there has been steadily increasing interest in performing machining operations dry or near-dry; MQL technology was therefore developed.

MQL machining applies MWF in the form of mist (with compressed air) and delivers it through spindle to the tool-workpiece interface for maximal lubrication and cooling. Compared to traditional wet processes, MQL requires only 10-100 mL/h, dependent on the particular cutting operations. Fundamental research in milling, turning, and drilling has confirmed that MQL can perform equally or even better than the wet condition in medium range of cutting processes, such as milling, shallow drilling on aluminum, cast iron, etc. [5-6]. However, due to thermally-induced problems, it is still technically challenging for high-speed, high-energy cutting, such as grinding, deep-hole drilling, particularly for hard-to-machine metals like compacted graphite iron (CGI), titanium alloys, and nickel-based alloys. To enable 100% implementation of MQL, automotive industry has started more proactively engaging in the MQL research and collaboration with academic institutes for developing the next-generation production processes.

Industrial experiences have concluded the advantages of MQL in power consumption, environment (emission, waste), chips recycle value, safety, and flexibility [7], as well as the major challenges including thermal issues (expansion, wear, and firing), tool development (through spindle/tool), and chips removal. The information is well-known in industry but rarely distributes to the academia and general population. As such, this paper aims to summarize the knowledge about the current status and future directions of MQL based on both industrial experience (Ford) and academic studies in public domain. In this paper, Sec. 2 first presents the historical background of Ford's implementation of MQL to reflect the rapid change in automotive industry. It is followed by quantitative measures of advantages in several domains. Section 3 introduces the production level MQL system and advancement as it is an important factor in MQL implementation. Finally, challenges and derived research opportunities are listed in Sec. 4, followed by the conclusions at the end.

2. MQL Implementation in Automotive Industry

Ford began investigating alternatives to conventional flood coolant machining technology for aluminum materials in the 1990s. In the U.S., Ford was engaged in a collaborative project seeking to completely eliminate coolants with an aim towards completely dry machining of aluminum. (Note: many machining operations for ferrous components were, and remain, dry.) During that same time period, a collaborative project was underway in Europe exploring MQL technologies. Completely dry machining was not successful for hole making operations (drilling, reaming, and tapping), but MQL was successful for this class of cutting operations. Development efforts were then focused to "industrialize" MQL technology and address the numerous process elements required for high-volume production (for example, chip management, thermal management strategy for machines and parts, optimized tool designs for MQL fluid delivery, MQL delivery system design optimization and reliability improvement, and dust/mist management). This development was driven through extensive laboratory trials and a series of small-scale production pilots in early 2000s.

The first automotive machining operation for which MQL was widely used was crankshaft oil and cross-hole drilling in the early 2000s [8]. The majority of other crankshaft rough machining operations are performed dry for cast cranks. MQL drilling could be done at significantly higher penetration rates in this application, reducing cycle time and machine investment. MQL implementation was relatively straightforward since the operation was generally performed on dedicated equipment without in-process tool changes.

Ford began applying MQL to aluminum transmission components in 2005, and by 2008 had over 200 MQL machining centers in operation machining aluminum transmission cases, torque converter housings, and valve bodies at two plants in North America. MQL machining is Ford's current standard machining method for these components, and is being implemented in new high-volume machining lines globally. Ford began machining aluminum engine heads and cast iron engine blocks at two plants in Europe in 2011; as in the case of transmissions, MQL is now the primarily standard method for machining cast iron engine blocks and aluminum engine blocks and heads, although wet machining is still used for some specialized operations. New engine MQL modules are being installed in Brazil and China.

In the global automotive powertrain machining, MQL cross hole drilling is standard for most high-volume crankshaft applications. MQL machining for aluminum engine blocks and heads and for aluminum transmission cases is more widely used in Germany than in North America. MQL is also widely used in Japan, but details of specific installations are often not available. Ford's future strategy is to extend MQL machining to additional operations in which they provide significant benefits. Areas of extension currently under investigation include CGI engine block machining, thermally sprayed engine bore machining, and aluminum deep hole drilling.

3. Advantages

The primary benefits from MQL include costs, energy consumption, environment, and chip recycling, which are summarized individually below.

3.1. Costs

The MWF associated costs including equipment, treatment, disposal, and safety and are important drivers in the overall cost of a machined component. Within powertrain operations, the costs related to MWF are in the range of 10-17% of the total manufacturing cost [4]. A case study of a transmission housing shows that the coolant related costs are as high as $2 per unit (without considering depreciation). By comparing two identical transmission modules for a 10 year cycle analysis including downtime cost, maintenance, operating cost, and floor space, study shows over 15% savings on a dedicated MQL machine tool, as shown in Fig. 1 [4].

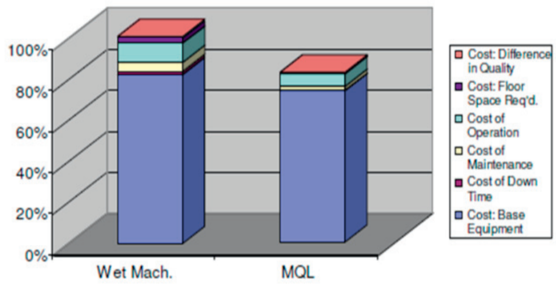
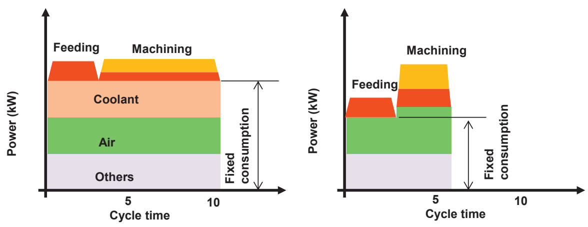


Fig. 1 Life Cycle Analysis of wet vs. MQL machining for a specific transmission part [4]

A conventional MWF system consists of filtration equipment, chillers, piping and pumps; thus the major cost-saving is from elimination of water-based MWF. The capital investment of MQL equipment and annual operating cost can be offset through lower MWF, water consumption, reduced filter media and disposal, lower compressed air use, and reduced waste water treatment. Other savings include reduced air emission, handling of wet, contaminated chips, and over all power consumption.

3.2. Energy

The largest energy consumptions in wet CNC machines are cutting process (~25%), MWF system (30-40%), and compressed air (15-20%). MWF associated energy consumption is significant in all machining processes. Fig. 2 shows an ideal energy map between a wet process and MQL. In traditional wet machining, the energy consumption is mostly fixed and can only be reduced by improving the cutting efficiency and decreasing the cycle time. For MQL, however, the MWF related energy no longer exists, which automatically results in saving in energy. With further advancements in through spindle and through tool design, MQL machining can achieve higher throughputs than wet approach in many applications, especially in aluminum machining. For example, a study in comparison of drilling oil holes in crankshaft (nodular cast iron) using gun drill and through-tool twist drill showed that MQL can yield tool life equivalent to gun drills at higher penetration rates [8]. As a result, although the machining power and air output in cutting could increase, the overall energy decreases with the cycle time as shown in Fig. 2(b). However, MQL requires increased compressed air use compared to wet machining, which may reduce the energy benefit achieved through cycle time and MWF pumping improvements.

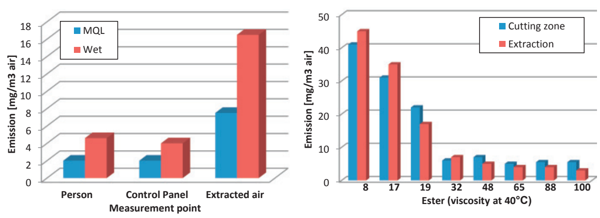


(a) (b)

Fig. 2 An illustration of energy consumption between (a) wet and (b) MQL conditions for an identical process (source: Horkos corp.)

3.3. Environment and Safety

Machining with MQL is generally viewed as a low-emission process due to a considerable reduction of MWF exposure in the inhaled air or on the skin compared to the wet machining. One potential concern is the decomposition and pyrolysis products due to high temperature of MQL machining. A study, done by German government, on measuring the emission during turning a steel revolver nut under MQL and wet conditions has confirmed that concentrations in more than 95% of the areas are less than half of the flood MWF baseline values and well below the threshold for the inhalable fraction (10 mg/m^3 air), as shown in Fig. 3(a) [9]. For MQL itself, a separate bench test found that thin, low-viscosity lubricants (< 20 mm^2/s) generate high emission values, shown in Fig. 3(b). The emission level is also proportional to the amount of fluid entering the system; thus optimizing the flow rate for a certain machining process can further improve the air quality.



(a) (b)

Fig. 3 Comparison of aerosol emission during machining (a) between wet and MQL turning and (b) among different MQL viscosities [9]

On air filtration requirement for occupational safety, MQL produces fine aerosol mist, usually less than 5 μm or sub-μm scale, compared to wet machining where the particle size ranges from 5-10 µm, based on a study from General Motors [10]. Small droplets tend to stay suspended in the air longer, more easily inhaled to the human body, and more difficult to remove with mist collectors. As a result, a high-efficiency particulate absorption (HEPA) filter is needed to trap the vapors and fumes. In addition, such neat oil system would require spark arrest and fire suppression. Note that the droplet size is not constant under MQL; it varies based on the machining settings, fluid flow rate, and fluid viscosity [10,11].

At Ford, a study on quantifying MQL emission has also been completed on three types of materials (steel, cast irons, and cast aluminum) under deep-hole drilling, which is considered the worst scenario in MQL application due to concentrated heat [12]. The air samples were collected from machining zone, filtered exhaust, and plant air for examination. Total airborne particulate concentrations in the plant air were found at least an order of magnitude less than the lowest Ford Occupational Exposure Limit (OEL) (1 mg/m^3) and US Occupational Safety and Health Administration (OSHA) Permission Exposure Limit (5 mg $/m^3$). For the potentially hazard chemical compounds in the plant air, concentrations of detected volatile organic compounds (VOCs) were found 50-times lower than their respective OELs. Concentrations of detected polycyclic aromatic hydrocarbons (PAH) were generally several orders of magnitude lower than the OELs. Overall, production air filtration is capable of removing 98-99% of particulates and hydrocarbon emission, which indicate an appropriate working environment for MQL plants.

3.4. Chip Recycling

Metal chip processing is a common practice in manufacturing to collect and treat metal wastes (e.g., chips) for recycling. Revenue from chip re-melting is often a significant component of a plant's operating budget. In wet machining, chips typically must be dried before transport to a remelter to avoid contaminating roadways. Chip drying is expensive as it requires energy and floor space.

During MQL machining, the metal chips produced are nearly dry and virtually clean. The near-dry chips do not require drying and thus bring more net revenue to the plant.

3.5. MQL Systems and Tool Designs

A variety of hardware systems have been developed for MQL applications. Depending on the delivery setup to the cutting site, lubricants can be applied with an external nozzle or a through spindle, internal channel. External supply is easy to use, implement, and requires no special tools; however, it is inadequate for deep-machining because tools are hidden in or behind the workpiece. Also, it requires manual adjustment to accommodate different tools to ensure oil coverage at the cutting edge. In high-volume manufacturing, the mist is usually delivered internally through the spindle and cutting tool. This way provides maximum lubrication. The major drawback for one-channel systems, in which the oil and air are mixed outside the machine and routed through the spindle, as shown in Fig. 4, is that this system produces larger droplet size due to long traveling distance for the aerosol stream. Also, the mist quality is unstable because of inertial and centrifugal force when delivered to the cutting tool tip, particularly for smaller oil holes in the tool. Studies have also shown that finer and stable mist is preferred in machining processes because of better lubrication and heat dissipation [11]. However, one-channel system is still popular for gantry machines, saws, etc. as those processes do not require precise control over machined dimensions and machinability.

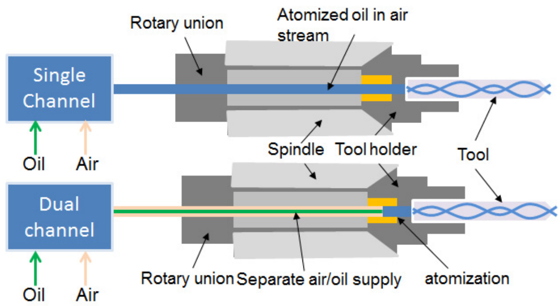


Fig. 4 Schematics of MQL systems: a single channel system and a dual-channel system

In contrast, dual-channel systems in which air and oil are mixed near the tool point are more robust in general operations. Ford is currently using this type of system in machining aluminum prismatic parts, such as transmission cases and valve bodies. Oil and air are routed in two parallel tubes through the spindle and mixed close to the tool holder. This way makes less dispersion and dropout of the mixture and delivers the mist with finer and more uniform than single channel systems, especially for high spindle speed where centrifugal force becomes significant. Also, dual-channel systems have less lag time when changing tools between cuts or changing flow rate during a cut, which is beneficial for machining centers that run multiple tools. The disadvantages are restricted supply base (e.g., Horkos, Bielomatik, and Unist) and high-cost to retrofit the spindles. Even if the machine was designed for internal, through-tool cooling, it does not mean that it will work perfectly with dual-channel system. For example, currently MQL specific tool holders are only hollow tapered shank (HSK) style; the rotary union needs to run dry; and the spindle needs to have enough room for dual pipes.

Tooling design is another factor in MQL advancement since oil mist must reach all the cutting edges, particularly in multiple-step tools. Through spindle application is common in drilling, reaming, and milling. When applied to MQL, the existing ports of a drill's coolant holes need to be redesigned to help deliver mist to the entire rake face for built-up and thermal damage prevention. Ensuring proper lubrication to all edges is much more difficult than for wet tooling, and often involves trial-and-error testing to determine required fluid passage sizes and angular relationships. For a modular cutting tool, specific design is required when machining the MWF channels to ensure the mist quality. The holes are usually machined by EDM and optimized in terms of diameter, branching, and outlet position for maximum mist output. General rules are summarized in Table 1. Practically, because of advanced technology and experience involved in the tool development, there is restricted supply base.

Table 1 Rules for through-tool channel design for MQL (source: Komet)

No right angle turn at the coolant outlet or inside the coolant channel		
No cavity within or between the coolant channels		
The coolant channel should be as large as possible		
The coolant outlets should design in a way to enable maximum oil coverage at the cutting edge		
Channel transition should be tapered instead of a step structure		

To confirm the proper mist generation, a spray pattern test is a simple and common method in industry to examine the tool. A sample tool is placed in a machine's spindle (MQL) and an absorbent medium green or blue surface is positioned about 1.3 mm in front of the tool, underneath, or around the tool as it rotates. If the spray pattern aligns closely with the cutting edges location, then there is a high probability that the tool can function properly.

4. Challenges and New Technologies

Bottlenecks of MQL fall in four areas: deep hole drilling, energy intensive process (e.g., grinding), difficult-to-machine metals (e.g., titanium, Ni-based alloys, thermally sprayed coatings), and special operations like honing and small hole drilling. Although MQL has been reported to provide superior lubrication, it generally does not have comparable cooling and chip evacuation abilities to those of wet machining. Without flood of MWF, accumulated heat can wear the tool and thermally distort the part. Without MWF flushing the cutting zone, chips can easily build up and clog in narrow operating regions. As a result, these issues can become major barriers that limit the MQL applications in aforementioned areas.

Deep-hole drilling (DHD) usually refers to making holes with the aspect ratio larger than 10. Common operations include oil and oil gallery holes in engine blocks and crankshafts. Aluminum DHD is currently generally feasible but still needs further research to optimize the settings and reduce the problem with cutting edge built-up. DHD in high strength cast iron is technically challenging. Our study has confirmed a large amount of heat generated not only at the cutting edge but also from the side of the drill due to chips and friction [13]. Under a low spindle speed, chips jam inside the hole, due to lack of momentum, thus creating tremendous torque and heat to cause tool breakage or hole distortion. One common industrial solution is applying an air booster to the MQL system, which tunes the system input air from 5 bars to 10 bars. Temperature and torque data in drilling 10 mm by 200 mm deep hole of cast iron has shown a significant improvement with air booster when chip clogging occurs, as presented in Fig. 5 [14]. Despite the advantages, high-air pressure also brings in three concerns: the MQL system must be designed to operate at higher air pressures, additional energy required to compress the gas, and noise is increased by the increased use of air. All of these could increase manufacturing costs, which defeats the intention of using MQL.

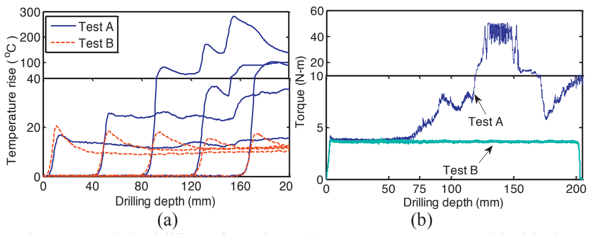


Fig. 5 Deep-hole drilling of cast iron: (a) temperature measured inside the workpiece along the drilled hole (1.5 mm from hole margin) and (b) torque. Tests A and B were performed with and without air booster, respectively.

For high-energy-intensity processes or difficult-to-machine metal machining, suppressing heat is the key element to realize MQL. Based on a similar concept of coolant reduction, in recent years, two types of MQL-like technologies have become available: Supercritical-CO_2-based oil ($scCO_2$) and Liquid Nitrogen (LN) technology (a.k.a. cryogenic machining).

The $scCO_2$ is an industrial solvent traditionally used in dry-cleaning to dissolve oil. This characteristic has been turned into a technology in machining processes where better oil penetration can be achieved. Briefly, the liquid CO_2 is pumped to supercritical phase (31°C, > 7.6 MPa (1100psi)), and lubricant is added to reaction chamber, dissolved in $scCO_2$. When the $scCO_2$-oil mixture delivers to the tool tip, gas expansion also generates cooling because of Joule-Thomson effect besides lubrication [15-17]. Studies have been conducted at Ford to evaluate $scCO_2$ and concluded a few promising results for this technology. For example, in drilling wear test on CGI, the flank wear can be reduced to half or less compared to the regular dual-channel MQL system. In turning experiments on Inconel, lower or equal tool wear was found compared to wet processes even at 25-45% higher material removal rate [17]. Some other tests (not published) also demonstrated that $scCO_2$ can reduce the diffusion wear when polycrystalline diamond (PCD) inserts is used for cutting ferrous materials. However, concerns with this technology are the cost of retrofitting the spindle, extra energy consumption in compressing CO_2, and the system reliability.

In contrast, technology for cryogenic machining has developed to a more mature status. Production CNC machines equipped with LN supply are available in the market provided by MAG-IAS, named minimum quantity cooling (MQC) technology. LN at -196°C is delivered through spindle, directly to the tool tip and cutting zone. Prior cryogenic applications sprayed LN at the cutting area acting as super coolant, while MAG's MQC emphasized a refrigerant application, which enables the cutting tool to remove the heat as a heat sink. Testing data released by MAG have demonstrated longer tool life in machining titanium alloys than a conventional wet process.

The concern for LN technology is that nitrogen cannot well dissolve and carry the oil, so LN is essentially only cooling with limited lubrication, though an additional oil line can be added to the LN system to address this limitation.

5. Conclusions

MQL has revolutionized the traditional wet automotive powertrain machining owing to its significant cost-saving in manufacturing. This paper summarized the development history at Ford, advantages, technical challenges, and advancements of MQL technologies based on industrial and academic experiences in the past decades. It was learned that the majority of savings was from the elimination of flood cooling and associated equipment and floor space. Significant reduction of waste water and thermal degradable emissions made it a sustainable and environmentally benign process. The automotive industry is being active in MQL development and implementation; aerospace manufacturers have also started research and implemented MQL in a few operations.

With the increasing demand on a variety of applications, technical challenges have become inevitable en route to full MQL implementation. Two major challenges during MQL machining are limited cooling and chip-evacuation ability as mentioned in Sec. 4, which lead to difficulty in dealing with difficult-to-machine materials and processes like deep-hole drilling and grinding. The next-generation MQL should be aimed at resolving these two issues, and meanwhile minimizing the additional energy and equipment costs on the fluid delivery system itself. The ultimate goal is to create a clean, sustainable, and high-efficient production environment.

Acknowledgements

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